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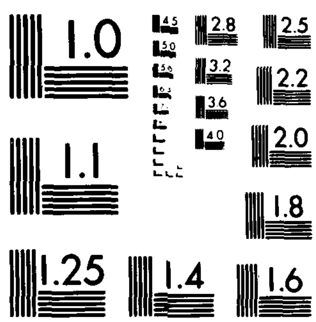

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The Significance of Defects on the Failure of Fibre Composites

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NORTH ATLANTIC TREATY ORGANIZATION

ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

AGARD Report No.690

THE SIGNIFICANCE OF DEFECTS ON THE FAILURE OF FIBRE COMPOSITES

by

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Paper presented at the 53rd Meeting of the AGARD Structures and Materials Panel held in Noordwijkerhout, the Netherlands on 27 September–2 October 1981.

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PREFACE

Composite materials are characterized by highly attractive physical properties which justify the presently fast increasing development in aerospace vehicles.

On another hand, they can suffer, like every structural material, from some loss of integrity which can occur

- *either* by defects or flaws initiated in the course of the production process and revealed at the final quality inspection,
- *or* by local damage in service, due to excess loading, by mishap or from environmental hazards.

The present technology of non-destructive inspection in general enables attention to be drawn to such defects but the knowledge which would allow a decision on the type and extent of defects that can be accepted is scarce; in other terms, what their consequences are on the load transfer capacity or on the future resistance to environment of the affected components.

The present attitude of manufacturers and operators of composite parts is to attempt to elude the problem by exercising a policy of severity, leading to discard or rejection of any suspected component, often far below the level of reasonable risk.

It is without doubt that such a costly practice will, in the long run, be prejudicial to the acceptance of composite materials and will handicap their development.

The proposed action of the AGARD-SMP is to organize a Specialists' Meeting, the aims of which, scheduled for Spring 1983, is to attempt to draw some guidelines for a more comprehensive qualification policy, supported by the experience already gained, the progress of inspection procedures and of analysis methods.

Dr Bishop reports hereafter the extensive experimental work presently carried out in government research establishments of the United Kingdom, and the results already obtained. The survey includes combination of environmental and loading conditions, the influence of typical defects, studied on test samples and, when available, on actual aircraft components.

As a pilot paper for the scheduled Specialists' Meeting, this remarkable contribution clearly defines the range of low significance defects and the directions where a particular attention has to be paid.

G.JUBE
Chairman of the
Composite Materials Sub-Committee

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THE SIGNIFICANCE OF DEFECTS ON THE FAILURE OF FIBRE COMPOSITES
(A review of research in the United Kingdom)

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SUMMARY

In the United Kingdom, research on defects in composites is being carried out in government research establishments, aerospace industries and universities. Defects produced during manufacture, cracking produced during loading and in-service damage such as impact have been studied together with their effects on mechanical properties and their implications for structural design. There is also work modelling the behaviour of notched composites and on the design of composites to give improved toughness and increased tolerance to damage.

A review of research in the United Kingdom is given based on papers presented at a meeting of the Institute of Physics held in November 1979 on "the significance of defects on the failure of fibre composites" and on more recent work.

1 INTRODUCTION

An understanding of the influence that manufacturing defects and defects which arise during service have on the performance of fibre composites is important if the material is to be exploited fully in structural applications. In November 1979 a one-day meeting[1] on "The significance of defects on the failure of fibre composites" was organized by the author for the Institute of Physics. Since then many of the papers presented at that meeting have been published in the open literature. Experience from this meeting has been used as a basis for reviewing the work on defects in the United Kingdom together with more recent work on the subject. A few results representative of the work done by each worker have been selected by the author for inclusion in this review; for a fuller picture reference should be made to the list of publications following this paper.

2 MATERIAL DEFECTS PRODUCED DURING MANUFACTURE

At British Aerospace, Weybridge, an assessment has been made by F.E. Rhodes[2] of the effect that manufacturing defects can have on the mechanical performance of carbon fibre reinforced plastics. Because of its relevance, this work is discussed in some detail. The following types of defects have been studied:

(a) microcracking due to differential thermal expansion of layers and exposure to moisture and subzero temperatures,

(b) gaps between tows which produce resin rich seams parallel to the fibres,

(c) distorted fibre tows,

(d) broken (or cut) fibre tows,

(e) inclusions, in particular swarf or pieces of backing paper off preimpregnated layers,

(f) voids, and

(g) glass tracer thread (not strictly a defect but introduced for radiographic checking).

Standard interlaminar shear strength and flexural tests were used to assess defects in unidirectional laminates. Thinner laminates, made of three layers orientated at 0°, $+45^{\circ}$ and -45°, were assessed in tension or compression as the outer skin of a sandwich beam under four point bending; the face of the beam not under test was made thicker to ensure that failure occurred in the skin under test. The majority of tests were carried out in compression since this was expected to be more sensitive to defects. In some cases, the static strength of sandwich beams was compared with the residual strength following 350000 cycles of fatigue at constant amplitude from 0 to 50% of the static strength of the control specimens without defects.

Some results are shown in Figs 1-4. Voids, moisture and freeze cycling had little effect on flexural strength but decreased the interlaminar shear strength (see Fig 1). A reduction of about 16% occurred if the voiding was as high as 7%. Paper inclusions with exposure to moisture reduced the interlaminar shear by approximately 20% (see Fig 2); paper inclusions completely traversed the specimens and produced defects more severe than was likely in practice. With a distorted tow, the tensile strength of the thin skins on sandwich beam specimens decreased by 15% (see Fig 3) but a decrease of 25% occurred for a cut tow; the tow width was 8% of the specimen width. However a significant recovery in strength occurred in the latter case following fatigue; 0° crack growth reduced the stress concentration at the cut. The effects of various defects on the compressive strength of

the thin skins are shown in Fig 4. Gaps in the 0^{o} layer and glass tracers had no significant effect even after exposure to moisture or freeze cycling; there was a small decrease for a gap in the 45^{o} layer. A cut tow reduced the strength by about 11% but the residual strength following fatigue was only 7% below the control values. The most significant decrease was obtained for paper inclusions, which could not be detected by ultrasonic inspection. Decreases in compressive strength up to 25% were obtained and delamination failures occurred. However for a single 10 mm paper inclusion the decrease was only 10%.

Generally it was concluded that apart from cut tows none of the defects studied appeared to have major effects on structural properties. In compression, the effect of minor defects on strength is unlikely to be greater than 10%. However a significant reduction in interlaminar shear strength can be expected in regions of high void content.

In the Structures Department at the Royal Aircraft Establishment, R.T. Potter[3] has carried out a small programme of research to determine the effects produced by discontinuous and kinked plies in unidirectional carbon fibre reinforced plastic under tension. The mean stress at failure on the continuous plies is compared in Fig 5 for increasing numbers of discontinuous plies and increased ply kinking. Comparison with the failure stress for specimens without ply defects shows that in all cases discontinuous plies reduced the mean failure stress in the continuous plies by 15% due to a stress concentration effect which was independent of the number of discontinuous plies. A further reduction in the failure stress in the continuous plies occurred with kinking due to the decrease in load carrying ability of the kinked ply and increased stress concentration; the reduction was greater for increased amounts of kinking and it was associated with delamination as the kinks straightened out. An overall reduction of 28% was obtained for kinking around three discontinuous plies.

At the Atomic Energy Research Establishment, Harwell, N.L. Hancox[4] has studied the effect of low (<1%) and high (5 to 6.5%) void contents on changes in torsional properties of carbon fibre reinforced plastic when exposed at various temperatures to dry or wet environments. More water was absorbed by specimens with high void contents. Shear modulus, shear strength and angular deflection at failure were measured at room temperature or temperature of exposure (up to $100^{o}C$). In general the values of shear strength were about 30% lower for all specimens with high void contents; water had little effect. The shear modulus of dry laminates was reduced substantially by the presence of voids, but voids only had a small effect for wet specimens where the greatest reduction was caused by increased temperature of measurement. The changes in shear strength with moisture and temperature were reversible in all cases but the changes in shear modulus and angular deflection at failure were irreversible for specimens with high void contents although these properties were reversible when the void content was low. The effects observed were not fully understood but changes in bond strength and plasticity were thought to have an effect.

D. Purslow of the Structures Department at the Royal Aircraft Establishment has developed considerable expertize in the fractographic analysis of tensile failures in carbon fibre reinforced plastics[5], and has been able to obtain an understanding of the part that defects play in the failure. Fibre faults, the quality of the fibre-matrix bond, the fibre distribution, fibre misalignment, voids, in plane shear and tensile cracks and delamination all play a part in the fracture process.

Scanning electron micrographs of a fibre following tensile failure show diverging lines (or 'radials') on the failure surface radiating from the point on the fibre surface where fracture initiated due to a stress concentration; the stress concentration in the fibre may have been due to a defect or stresses induced by the near proximity or fracture of a neighbouring fibre. Fracture of one fibre leads to the sequential failure of neighbouring fibres and the fracture process can be followed through the composite following the 'radials' on each fibre.

Such a sequence of events can be seen in Fig 6 where fracture in this area initiated at a fibre defect. The fracture process follows several routes from the defect, crossing from one fibre to the next at the point where fibres are closest and the stress concentrations highest, *ie* the fracture follows the path of highest fibre density. Occasionally these paths meet giving rise to two sets of radials on one fibre. Thus a zone of fracture initiating at one defect can be identified. In the same specimen other such zones, which may have been formed simultaneously due to other defects, can also be identified.

Another such zone is shown in Fig 7. The fracture paths can be seen to be radiating from a region where two defects are present, a resin rich area and two misaligned fibres (Fig 8). Closer examination of the radials near the defects shows that the fracture process initiated at the misaligned fibres (see Fig 9) and not the resin rich area although this did influence the stress distribution in the zone and modify the fracture paths.

Once a full picture of the fracture surface is obtained, made up of zones of failure initiating at various points, it is frequently possible to determine the cause of failure in the composite. This is frequently at a defect and the defect may be a significant one. However it must be pointed out that many material defects can be considered part of the

heterogeneous nature of the composite material. In many cases the particular defect initiating failure may not appear to be any more significant than the thousands of other similar defects in the same material.

This expertise in fractographic analysis is being extended to other forms of loading and the growth of damage from barely visible impact damage is also being studied.

3 FIBRE DEBONDING IN GLASS FIBRE REINFORCED PLASTICS

At the University of Surrey, an interesting piece of research has been carried out by J.E. Bailey and A. Parvizi on fibre debonding effects in glass fibre reinforced plastics[6]. In a $0^{\circ}/90^{\circ}/0^{\circ}$ glass fibre epoxy laminate under tension in the 0° direction a small modulus change was found, associated with a visual whitening effect at a strain lower than that at which transverse cracking initiates in the 90° layer, see Fig 10. Observations with a scanning electron microscope of the specimen during loading showed that this change was due to fibre debonding in the 90° layer and the whitening effect was due to the cracks opening under load. Removal of the load caused the whitening effect to reduce due to crack closure but the modulus was not recovered, see Fig 11. Annealing the specimens at the curing temperature of 100°C so that the thermal strains were recovered and the fibre and matrix surfaces came together again, caused rebonding to occur and the original properties were recovered. With larger increases in strain more debonding occurred and cracks coalesced to form a nucleation point for transverse cracking. Similar debonding effects were not observed in glass fibre/polyester composites since debonding was already present in the manufactured composite due to the larger residual thermal strains. Further research is being carried out on this topic.

4 EFFECT OF MATERIAL VARIABLES ON NOTCH SENSITIVITY

Notch sensitivity parameters obtained from machined holes or notches can be used to assess the sensitivity of materials to stress concentrations produced by defects or damage in service. In the Materials Department of the Royal Aircraft Establishment, the author has investigated the notch sensitivity of carbon fibre reinforced plastics under tension. The growth of shear cracks and delamination at notches and holes in multi-directional laminates has been studied[7] using a laser moiré technique. Stored strain energy is released by the crack growth and the resulting zone of damage effectively blunts the notch or hole and reduces the stress concentration. The damage zone formed at a sharp notch is larger than that formed at a circular hole (see Fig 12) and the blunting effect is such that the failure stress of a composite containing such a sharp notch may not be very different from that for a circular hole. Thus the formation of a damage zone at a notch has a beneficial effect on notched behaviour under tension; the larger the damage zone the greater the failure stress.

The size of the damage zone depends on the shear strength parallel to the fibres, *ie* the fibre-matrix bond strength, and this has been varied by changing the fibre, the fibre surface treatment and the matrix. The size of the damage zone also depends on the lay-up and stacking sequence. Studies[8] of the interactions between layers have indicated that shear cracking parallel to load bearing 0° fibres always reduced the stress concentration in the 0° layer but cracks parallel to fibres at other orientations, while having the beneficial effect of releasing stored strain energy in a non-catastrophic way, increase the stress concentration in a neighbouring 0° layer. Delamination reduces these interactions and removes constraints on 0° shear cracking and this is beneficial. Delamination has been found to be increased by increasing the thickness of the layers[8]. In Fig 13 the notched failure stress has been plotted against specimen thickness for laminates with different layer thicknesses. It can be seen that the failure stress was increased by 50% by stacking four thin layers together to produce thicker layers. Increasing the laminate thickness by repeating the basic stacking sequence with thin layers had no effect. Thus the notch sensitivity of a multidirectional carbon fibre composite under tension can be reduced substantially by careful materials design. However it must be pointed out that shear cracking and delamination can reduce the material's compressive strength and fatigue performance. The effects on these properties are being studied in the Materials and Structures Departments at the Royal Aircraft Establishment.

Woven carbon fibre cloth offers many production advantages and with its increasing use in reinforced plastics a programme of research has been carried out[9] in the Materials Department at the Royal Aircraft Establishment to investigate the effect that woven cloth has on the notch sensitivity in tension. For a particular type of lay-up, *eg* (0°,90°), ($\pm 45^{\circ}$) or (0°,90°,$\pm 45^{\circ}$), there was no effect due to layer stacking sequence or the way the cloth faced in laminates made from five-shaft satin woven cloth (the dominant fibre direction in this weave is different on each side of the cloth). Results for laminates made with the woven material were compared with those for the equivalent non-woven lay-up made with unidirectional material. Effects which occurred with type of lay-up were the same for sharp notches and circular holes. Values of $\sigma_f\sqrt{\pi a}$ for sharp notches (σ_f is the notched failure stress and a the semi notch length) have been compared in Table 1; $\sigma_f\sqrt{\pi a}$ is a measure of the toughness of the composite, *ie* its ability to absorb stored strain energy non-catastrophically mainly by shear cracking and delamination. For 0°,90° lay-ups, the values were 30% lower for woven material partly because of the reduced volume fraction of fibres but mainly due to kinking of fibres in the load direction. However for $\pm 45^{\circ}$ lay-ups the values of toughness were the same for non-woven and woven material, indeed, the toughness for the same volume of fibre was more in the woven case.

Woven laminates with $0^\circ, 90^\circ, \pm 45^\circ$ lay-ups had toughnesses 20% lower than for the non-woven case mainly due to the reduced toughness of the 0°, 90° layers of woven cloth. As might be expected from the results for $\pm 45^\circ$ lay-ups, the toughness of $0^\circ, \pm 45^\circ$ laminates with 50% 0° layers was not significantly changed when woven cloth was used for the $\pm 45^\circ$ layers instead of unidirectional material and damage zones were observed to be the same size in both cases. The implications of these results are that woven cloth may be substituted for unidirectional material in $\pm 45^\circ$ plies, when under tension in the 0° direction, without increasing notch sensitivity and reducing toughness. Indeed, woven cloth may offer improvements in other properties, particularly where an area of damage must be contained although delamination between a layer of woven cloth and a neighbouring layer of woven or unidirectional material could still occur.

R.J. Lee and D.C. Phillips of the University of Bath and Atomic Energy Research Establishment, Harwell, respectively, have also been studying[10] the behaviour and strengths of notched and holed carbon fibre reinforced plastics. They also found that materials variables such as fibre type, bond strength, ply orientation, ply thickness and stacking sequence had an effect on the toughness of the material and some results for different lay-ups and stacking sequences are shown in Table 2. Again thicker layers generally produced more delamination and tougher laminates (compare results for lay-ups A and C and lay-ups D and E). However it was found that the $0^\circ, 90^\circ$ laminates were much tougher when the 0° layers were on the outside and splitting and delamination of 0° layers were not constrained by the 90° layers as they were in lay-up B. In-plane transverse stresses in the 0° layers resulting from the Poisson's ratio constraint imposed by neighbouring layers were found to affect toughness. It was calculated using laminated plate theory that for lay-up C the transverse stress in the 0° layers due to neighbouring 90° layers was positive whereas this stress in lay-up D with neighbouring $\pm 45^\circ$ layers was negative. Thus more constraint was imposed on the growth of 0° shear cracks by $\pm 45^\circ$ layers and the toughness of lay-up D was lower.

5 MATHEMATICAL MODELS FOR PREDICTION OF NOTCHED STRENGTH

Various mathematical models have been proposed for calculating the notched strength of carbon fibre reinforced plastics with the aim of predicting the effects of defects on damage. Lee and Phillips[10] have assessed the applicability of a variety of macroscopic failure theories recognising that the microstructural effects which had been observed experimentally were not incorporated in these models. The following models were considered and the predicted results compared with experimental results, see Fig 14:

(1) A linear elastic fracture mechanics approach with a correction for the damage zone,

(2) The 'inherent flaw' model due to Waddoups and co-workers where a hypothetical intense energy region adjacent to the notch is modelled as an inherent flaw,

(3) The 'point stress' model due to Whitney and Nuismer which assumes that failure occurs at a point ahead of the notch where the stress equals the unnotched strength,

(4) The 'average stress' criterion due to Whitney and Nuismer which assumes the stress ahead of crack is averaged over a characteristic distance, and failure occurs when this exceeds the unnotched strength,

(5) The stress concentration approach proposed by McGarry and co-workers which assumes that the notch with its damage zone behaves as an equivalent elliptical hole with a radius of curvature which is characteristic of the material.

For a highly notch sensitive laminate, the predictions for all the models were in close agreement with each other and with the experimental data. For the laminate with the lower notch sensitivity the agreement was not as good. The characteristic length associated with each model varied with the length of the notch and the geometry of the specimen which suggested that the parameters were not fundamental material properties. The linear elastic fracture mechanics model gave the best fit but it was concluded that the general applicability of all the models was questionable and there was still a need for a suitable predictive theory which correlated with the physical behaviour of the material.

R.T. Potter[11] at the Royal Aircraft Establishment has tried to incorporate the effect of microstructural behaviour at the notch tip into a failure theory which is similar to the equivalent ellipse approach but where stress gradient at the notch tip is the critical parameter which determines if adequate load can be transferred from fibre to fibre to break them in sequence and cause failure. He has compared his model with the 'average stress' criterion due to Whitney and Nuismer (see Fig 15) and has obtained good agreement in both cases with the experimental data for a laminate with thin layers. As with all the models difficulties arise for tougher laminates.

G. Dorey[12] has pointed out that although different physical mechanisms are used in the different models, they predict similar effects since they all depend on the form of the stress distribution ahead of the notch. He has demonstrated for several of the models

discussed here that they have the same form and have a $1/\sqrt{a}$ dependency. It is therefore not surprising that agreement between models is so close.

C.R. Chaplin[13] of the University of Reading has considered notch sensitivity under compression loading. He has demonstrated that unidirectional carbon-fibre composites are notch sensitive and that the growth of a compressive failure obeys similar laws to those for a tensile crack. In his experimental work the propagation of a shear band from an edge notch was controlled with a very stiff testing rig; crushed material in the shear band was thought to carry load during stable damage propagation. Crack resistance curves were obtained for the material and the crack resistance was found to vary as the damage grew and appeared to depend on the depth of the shear band. The initial value of crack resistance, which was similar for all specimens, was put into a polynomial expression of the form used in linear elastic fracture mechanics for a tensile crack, and compressive failure stresses of notched specimens with varying crack length were predicted, see Fig 16. Good agreement was obtained with experimental results.

The experimental value of the compressive strength of a unidirectional carbon fibre composite without machined notches is less than the tensile strength and lower than would be expected theoretically. Chaplin proposes that this is because this material contains inherent defects, and it is the sensitivity of the material to these small notches which causes the low strength.

Theoretical modelling of ply defects in fibre composites is at present being carried out by D.J. Cartwright at the University of Southampton under a MOD Contract. The problem is being considered, using collocation techniques, of a composite made up of two orthotropic sheets with a crack in one sheet, a debonded area between the sheets or both these defects. The growth of these defects is being modelled and their significance assessed. This work will be extended to multilayered composites where stacking sequence effects will be investigated.

6 IN-SERVICE DAMAGE

In the Materials Department at the Royal Aircraft Establishment, G. Dorey has been studying[12] the damage produced by impact and the effect this damage has on mechanical properties. The type of damage produced by impact depends on the incident energy, material properties and the geometry. No damage occurs if the energy of the projectile is accommodated by the elastic strain energy in the material. Simple calculations have been made of energies necessary to cause:

(a) delamination $(2/9)(\tau^2/E)(w\ell^3/t)$

(b) flexural fracture $(1/18)(\sigma^2/E)(w\ell t)$

(c) penetration $\pi\gamma td$

where τ is the interlaminar shear strength, σ the flexural strength, E the Young's modulus, γ the through-thickness fracture energy, d the diameter of the projectile, and w, ℓ and t the width, length and thickness of the flexed part of the test specimen. Whether delamination or flexural fracture occurs depends on the relative values of τ and σ and the span-to-depth ratio ℓ/t ; lower fibre-matrix bond strengths result in delamination at lower incident energies. Materials with lower moduli such as glass-fibre reinforced plastic can accommodate more elastic strain energy, and delamination or flexural fracture only occur at higher incident energies. Flexural fracture is less likely when there are low modulus layers on the outside, *eg* $\pm 45^\circ$ layers. Whether penetration occurs depends not only on the incident energy but on the size of the projectile; penetration is more likely for small masses travelling at high velocities.

The residual shear strength of specimens containing delaminations following low energy impact has been found[14] to be directly related to the delaminated area for a range of materials. Results are shown in Fig 17 for plain and hybrid reinforced plastics made with carbon fibres and Kevlar fibres. The shear strength τ is inversely proportional to the fourth root of the delaminated area A.

The residual flexural strength was found[12] to be dependent on the lay-up. Some results are plotted in Fig 18 for impact by a steel ball from an airgun. At low impact energies where delamination occurred there was a decrease in flexural strength. A further decrease occurred for lay-up B at incident energies of 3-4 J as a result of flexural failure of the outer 0° fibres on the back face; this decrease did not occur for lay-up A with $\pm 45^\circ$ layers on the outside. The amount of damage on the back face which occurred with penetration at higher incident energies lessened for lay-up B and a higher residual flexural strength resulted. Once penetration occurred the flexural strength was independent of the incident energy of impact for both lay-ups.

In Fig 19 the residual tensile and compressive strengths are shown for a different lay-up following dropweight impact[15]. Delamination at low incident energies causes no reduction in the tensile strength of the composite but a substantial decrease in the compressive strength due to local buckling. At higher impact energies, when fracture of the

outer 0° fibres occurred, the tensile strength also decreased but the overall decrease in compressive strength was twice as great. The effect of varying the fibre-matrix bond strength was investigated; the residual tensile strength was higher for lower bond strengths but the compressive strength decreased further.

This work is being extended to include an assessment of the fatigue performance following impact; the effect of varying material properties will be investigated with the aim of improving materials design.

At British Aerospace, Manchester, experience has been gained[16] of the influence that thermally-induced cracking can have on the performance of a carbon-fibre wing flap track. The experimental track tested was essentially an I beam constructed of CFRP with ±45° web channels bonded back to back and unidirectional capping strips (see Fig 20). The beam was supported at several points and loaded in bending by two rollers either side of a bridge support, the forward roller running in the channel of the I beam and the rear roller running under the beam. Strips of titanium were bonded to the working surfaces and fasteners inserted to prevent debonding of the titanium. The flap track was ideal for a study on defects since it contained features which induced damage and limited its propagation, *eg* large stresses at the interfaces between blocks of material with different moduli, holes, and complex loading in the angle where the web meets the flange.

The specimen as manufactured contained cracks at the holes in the capping strips (parallel to the fibres), which had been introduced during drilling, see Fig 21. These cracks extended when the specimen was cooled to -57°C unloaded but during testing were found to have no influence on the load carrying capability of the track. Indeed it was found that the fasteners were very effective in preventing delamination.

The damage produced during loading is shown in Figs 22 and 23. On loading to the design ultimate load (DUL) at ambient temperature, some delamination at the forward roller position was just detectable, when examined with ultrasonics, near the bond-line in both the flanges and the web; this delamination extended in the flanges and up and along the web when reloaded to the same load at -34°C. Subsequent loadings up to 180% DUL caused some further delamination at ambient temperature but most delamination was generated when loaded at -34°C. Failure of the supporting rig occurred when attempting to load to 180% DUL at -34°C due to reduced torsional stiffness of the flap track caused by delamination.

Earlier specimens which were manufactured with delamination at the interface between the web channel and capping strip and voids contents as high as 8% in some places withstood at least 150% DUL before failure. Fatigue tests on one of these specimens up to 75% DUL resulted in minor debonding only. Generally, the programme indicated that a working structure in CFRP can be made to tolerate much damage.

A preliminary investigation of the effects of defects in reinforced plastics made from woven carbon fibre cloth has taken place in an MOD Contract with the University of Salford under Professor B. Yates. The influence of impact, cut tows and delamination on flexural and tensile properties has been briefly investigated and it is hoped that a fuller programme of research based on this preliminary work will commence shortly.

7 CURRENT WORK ON DEFECTS IN STRUCTURAL ELEMENTS

Several research programmes investigating the significance of defects in structural elements are just beginning. The largest, at British Aerospace, Warton Division, covers various defects and damage in carbon fibre reinforced plastics alongside a comprehensive repair programme. Fibre discontinuity in the form of surface scratches is being assessed under tension for several different lay-ups. Skin delaminations at the edge or centre of a sandwich beam and skin-core disbonds are being investigated in compression by loading the beam in flexure. Delaminations in corner radii of angles are to be assessed under shear parallel to the angled edge. Also local hole defects in bolted joints are to be assessed. The hole defects to be investigated are incorrect countersink angle, delamination on drilling, scored hole such as that caused by a blunt dirty drill, oversize hole and incorrect bolt tightening. Impact damage will be simulated by creating areas of damage with and without holes in sandwich beams tested in compression. In many cases fatigue loading will also be applied to specimens to establish the growth rate of the defect. This programme is already underway and will be completed in two years; many results will be available before completion.

A further smaller programme is starting at British Aerospace, Weybridge which assesses defects in woven as well as non-woven carbon fibre reinforced plastics. Defects are being investigated in two structural elements, holes in bolted joints, and angles. The hole defects are similar to those in the programme at Warton. The angles formed from ±45° material contain voids, creases in the fibres and distortion in lay-up angle at the corner. The shear strength of the angle with defects and the residual strength following fatigue are being measured.

In the Structures Department at the Royal Aircraft Establishment, R.T. Potter is using an 'I' beam specimen under three point bend as a vehicle for studying a series of defects which may cause delaminations in a structure. In particular defects are being introduced in the web (±45° lay-up), at the corners and as disbonds between the cap (predominantly 0° lay-up) and web.

Also in the Structures Department at the Royal Aircraft Establishment a section tapered in the thickness is to be used for a fundamental study of delamination growth; the taper is slightly more severe than in the wing of the AV8B. The study will make use of many techniques, *eg* acoustic emission, moiré fringes, fractography and ultrasonic C-scanning techniques.

8 CONCLUDING REMARKS

A comprehensive programme of research on the effects that defects have on the performance of fibre composites has been underway for some years. Considerable expertise has already been gained and it has been shown that some defects have little effect on the composite properties whereas others can have a significant effect under certain loading conditions. In the near future the significance of most defects likely to occur during manufacture or in-service will have been fully assessed.

Table 1

TOUGHNESS PARAMETERS $\sigma_f\sqrt{\pi a}$ OF CFRP (MPa$\sqrt{m}$)

(S.M. Bishop, J. Hutchings)

Type of lay-up	Woven (V_f = 61%)	Non-woven (V_f = 66%)
0°,90°	28.7	44.1
±45°	21.8	20.4
0°,90°,±45°	27.1	35.0
Type of lay-up	**Mixed* (V_f = 63%)'**	**Non-woven (V_f = 66%)**
0°,±45°	40.9	42.2

* Mixed - 0° non-woven, ±45° woven

Table 2

TOUGHNESS PARAMETERS $Y\sigma_f\sqrt{a}$ OF CFRP* (MPa$\sqrt{m}$)

(R.J. Lee, D.C. Phillips)

Stacking sequence	$Y\sigma_f\sqrt{a}$
A $[0,0,90,90]_S$	56.5
B $[90,90,0,0]_S$	38.4
C $[0,90,0,90]_S$	43.0
D $[0,\pm45,0]_S$	33.0
E $[\pm45,0,0]_S$	56.5

* Y width correction factor

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* Presented in part or fully at Institute of Physics meeting[1].

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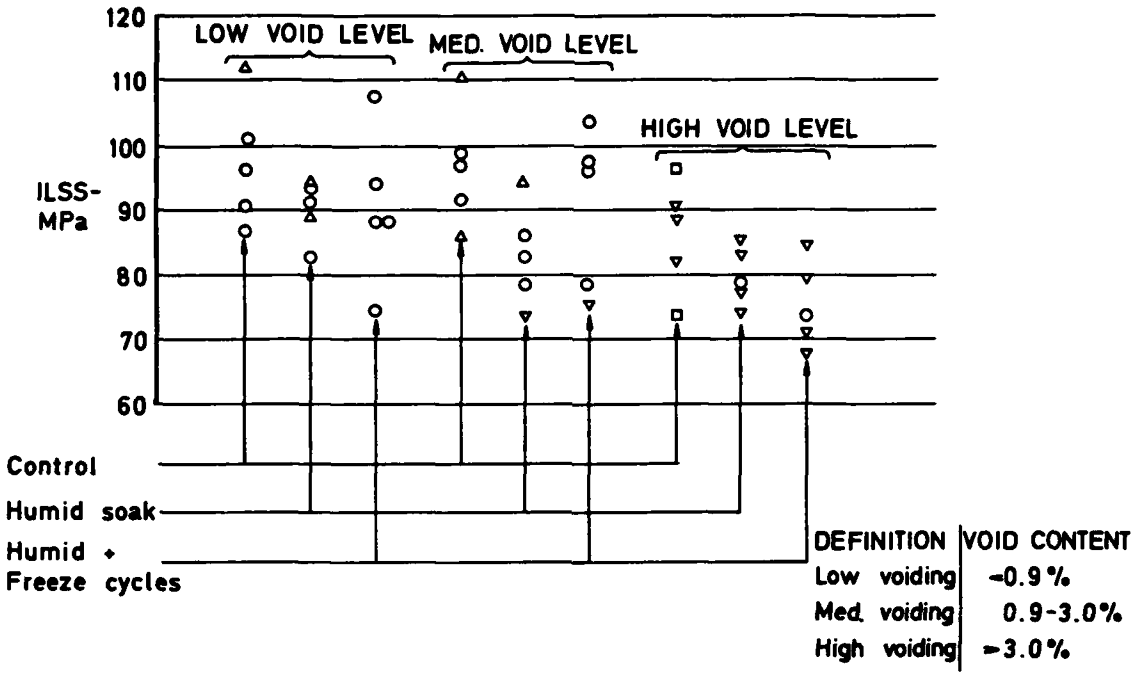

Fig 1 Variation of interlaminar shear strength with void content and preconditioning (F.E. Rhodes)

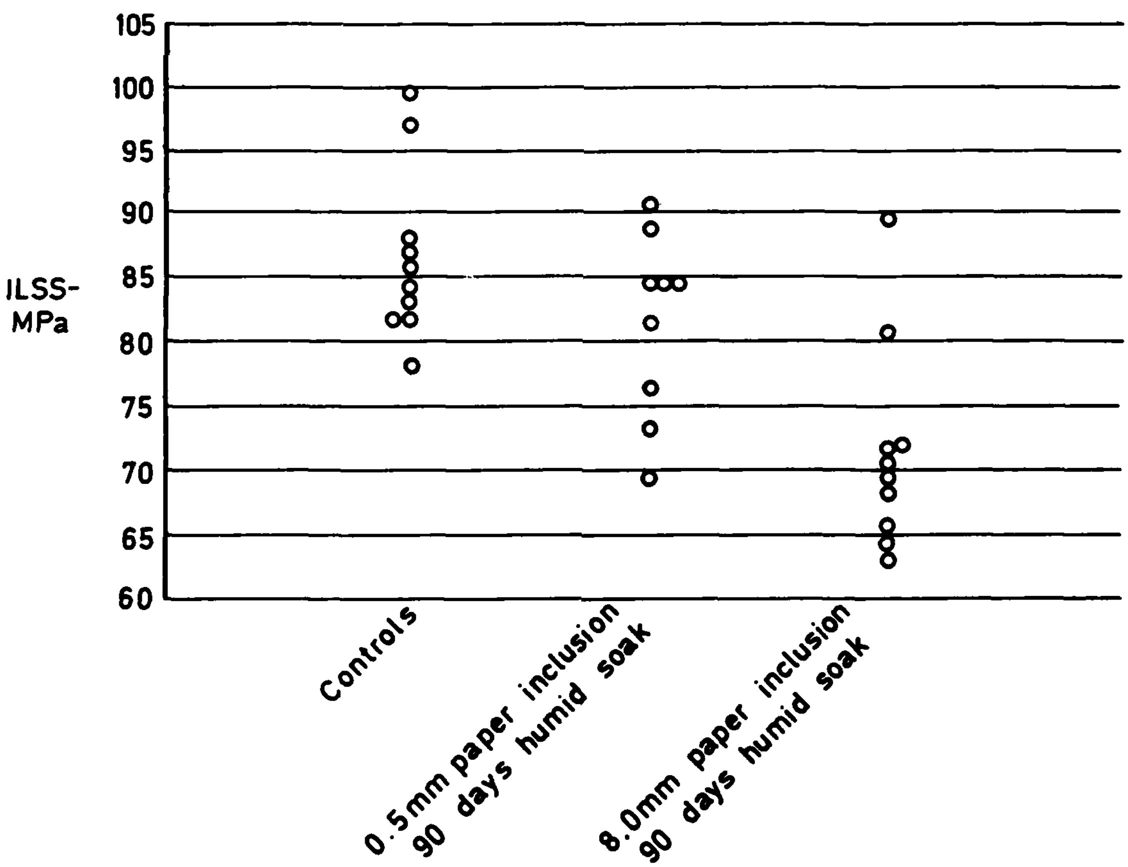

Fig 2 Effect of inclusions at mid-depth on the interlaminar shear strength (F.E. Rhodes)

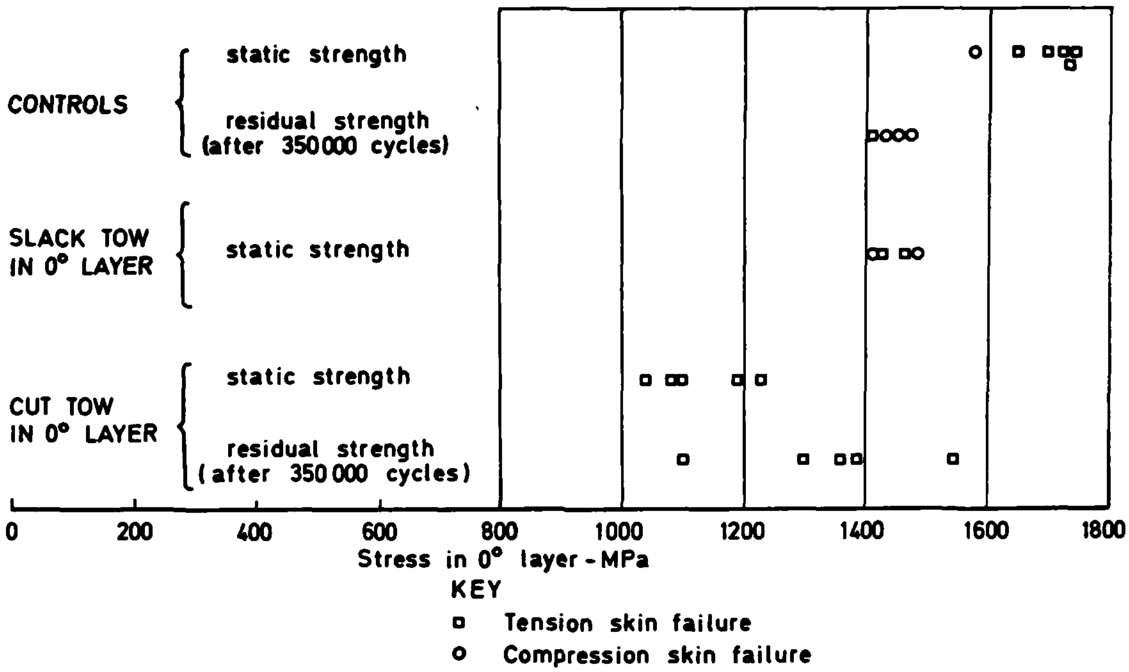

Fig 3 Effect of defects in 0^{o} layer on tensile strength of a $0^{o} \pm 45^{o}$ skin of a sandwich beam (F.E. Rhodes)

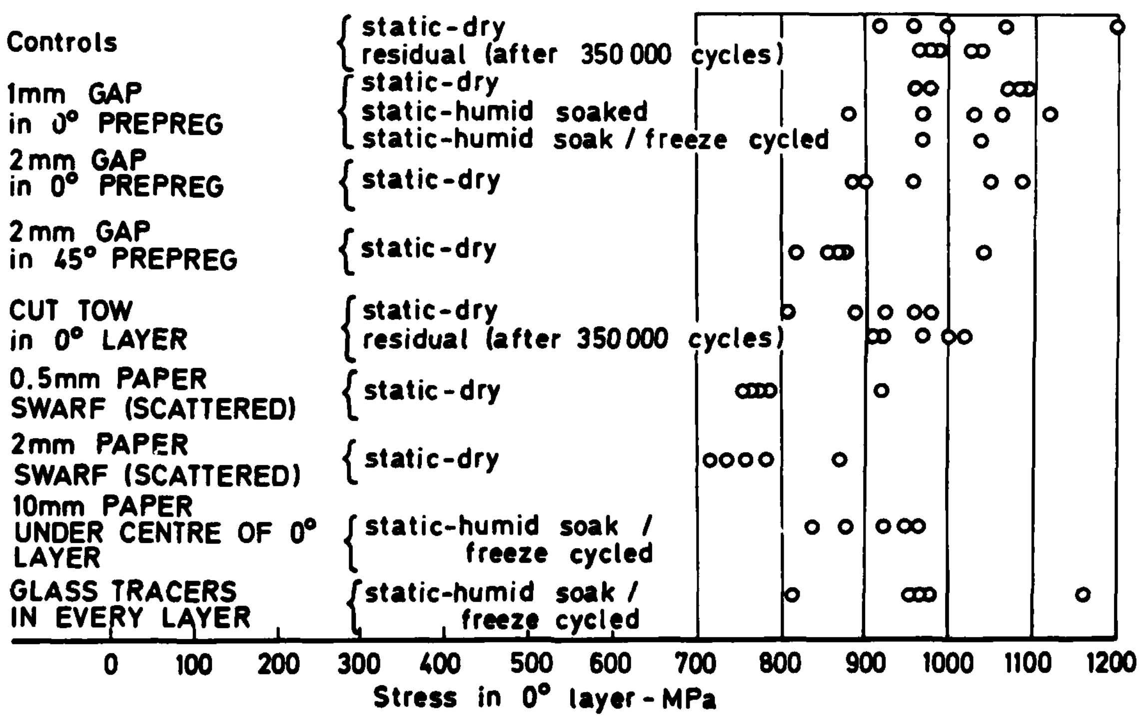

Fig 4 Effect of defects on compressive strength of a $0^{o} \pm 45^{o}$ skin of a sandwich beam (F.E. Rhodes)

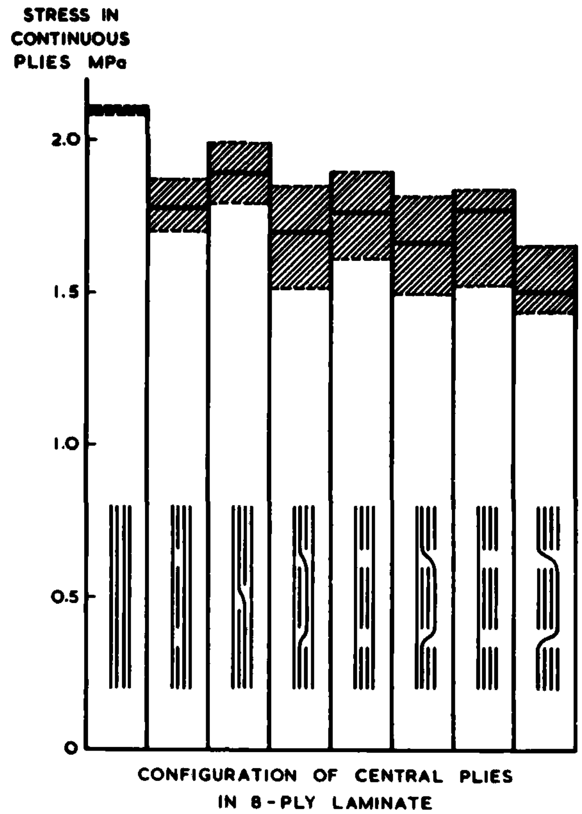

Fig 5 Effect of discontinuous and kinked plies on the tensile strength of unidirectional CFRP (R.T. Potter)

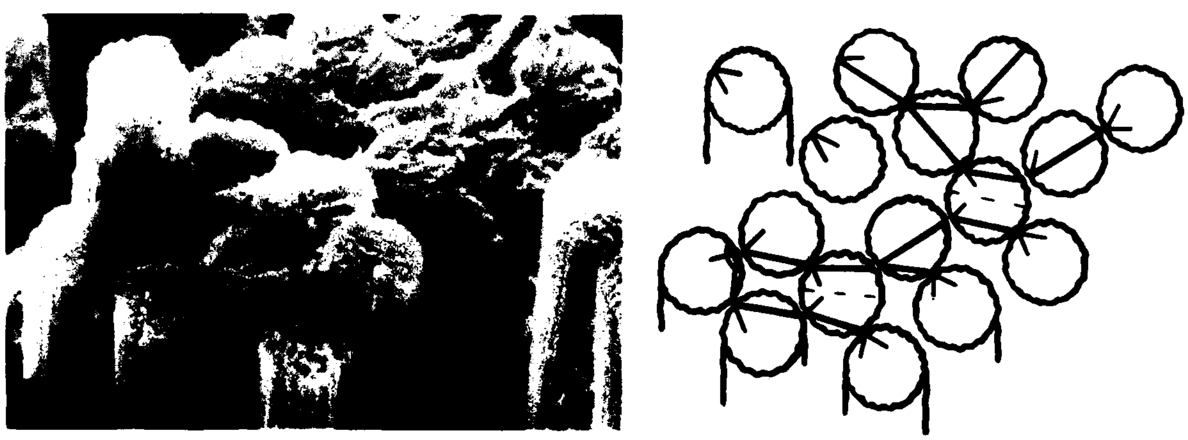

Fig 6 Fracture of CFRP under tension showing initiation at a fibre defect and subsequent path of fracture (D. Purslow)

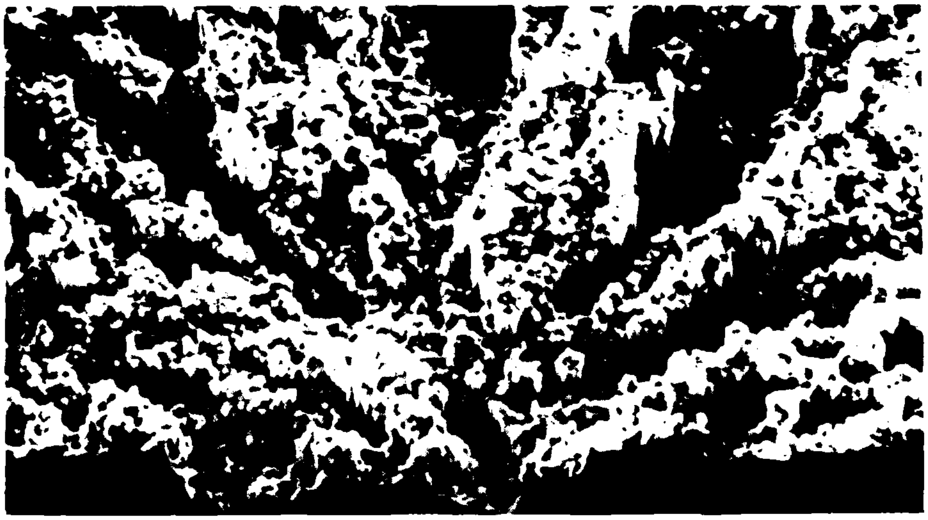

Fig 7 Fracture paths in CFRP diverging from one area of fracture surface (D. Purslow)

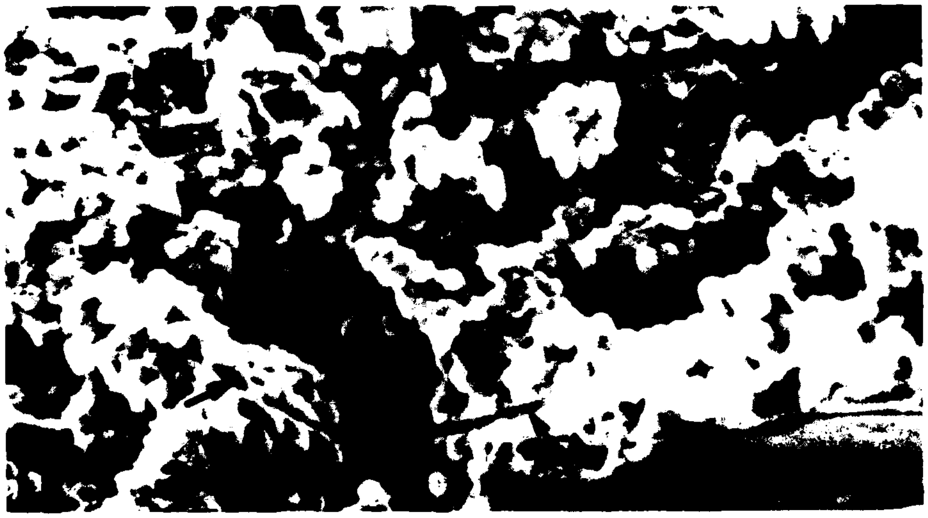

Fig 8 Area (in Fig 7) enlarged to show two defects, a resin rich area and misaligned fibres (D. Purslow)

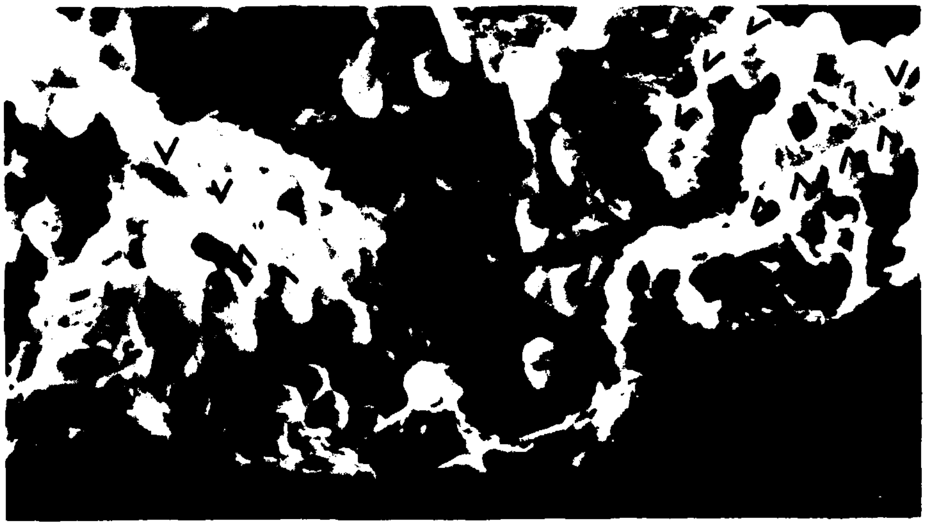

Fig 9 'Radials' on fibres indicating fracture initiated at misaligned fibres (D. Purslow)

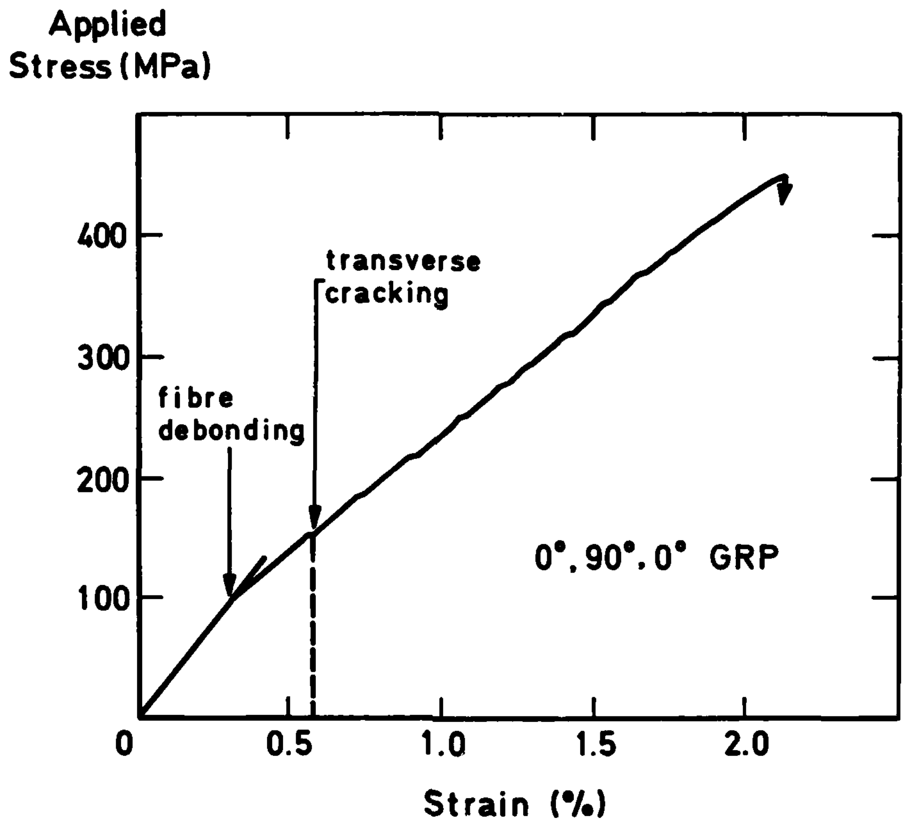

Fig 10 Stress-strain graph showing modulus change due to fibre debonding in a glass fibre epoxy laminate (J.E. Bailey, A. Parvizi)

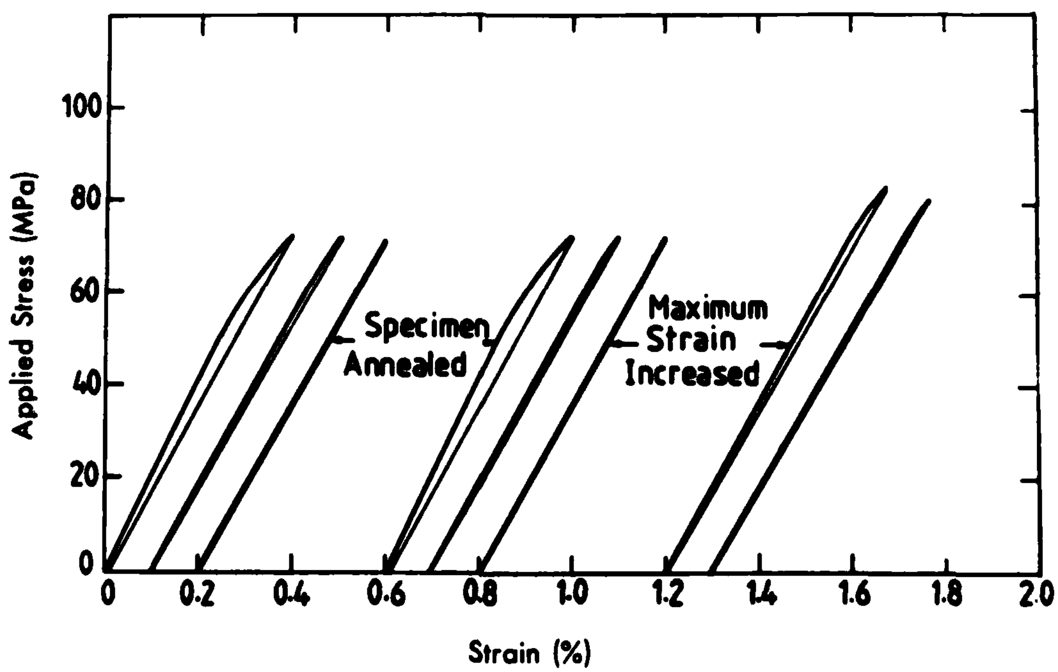

Fig 11 Loading/unloading curves showing disappearance of non-linear behaviour and subsequent recovery of properties with annealing (J.E. Bailey, A. Parvizi)

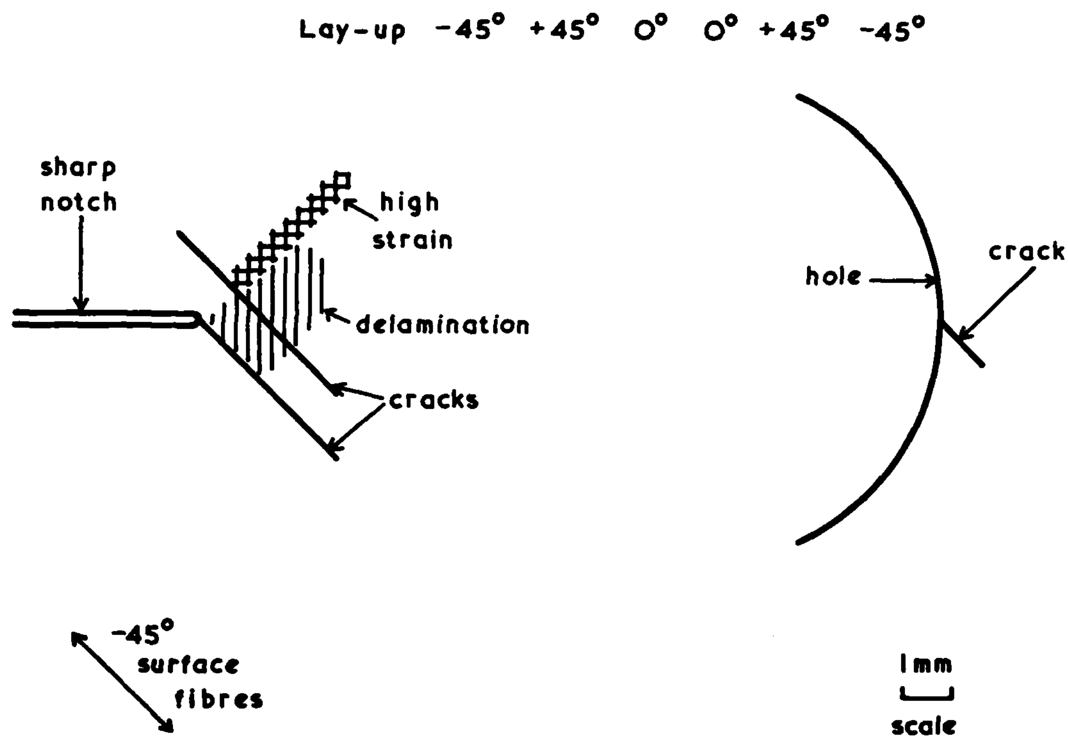

Fig 12 Damage zones at a sharp notch and a circular hole in CFRP under tension (S.M. Bishop)

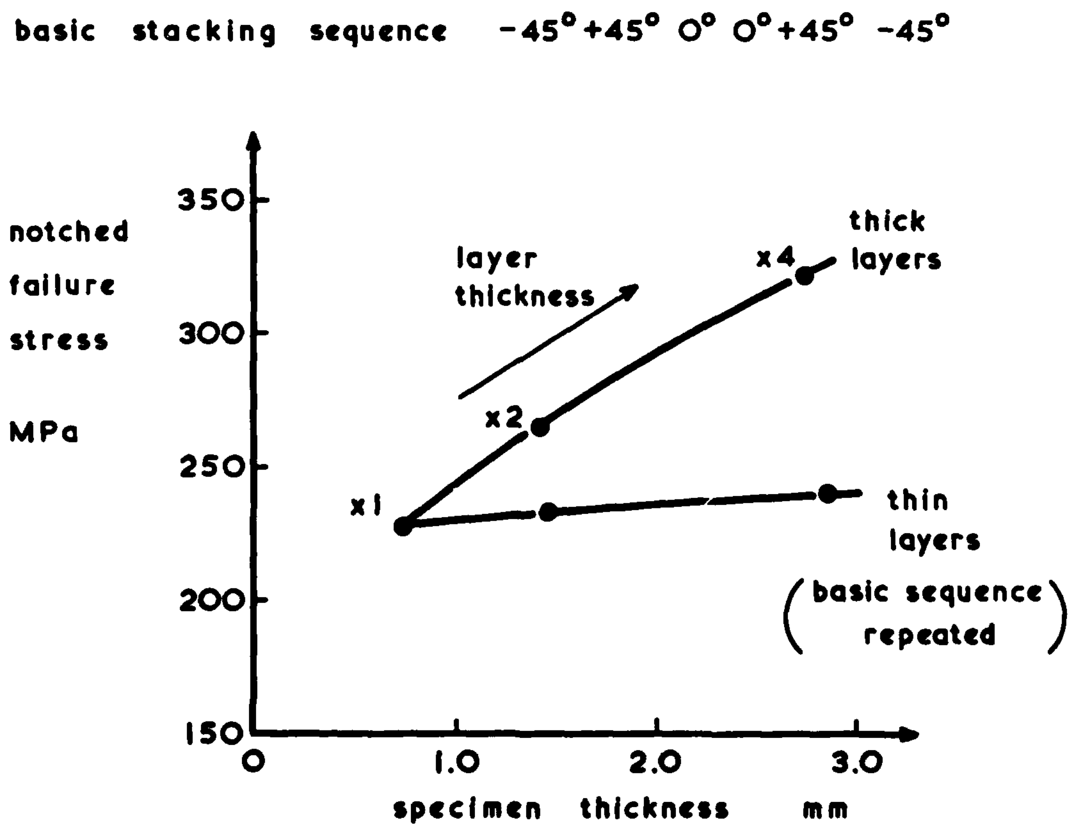

Fig 13 Graph showing increase in notched failure stress with increased layer thickness in CFRP under tension (S.M. Bishop, K.S. McLaughlin)

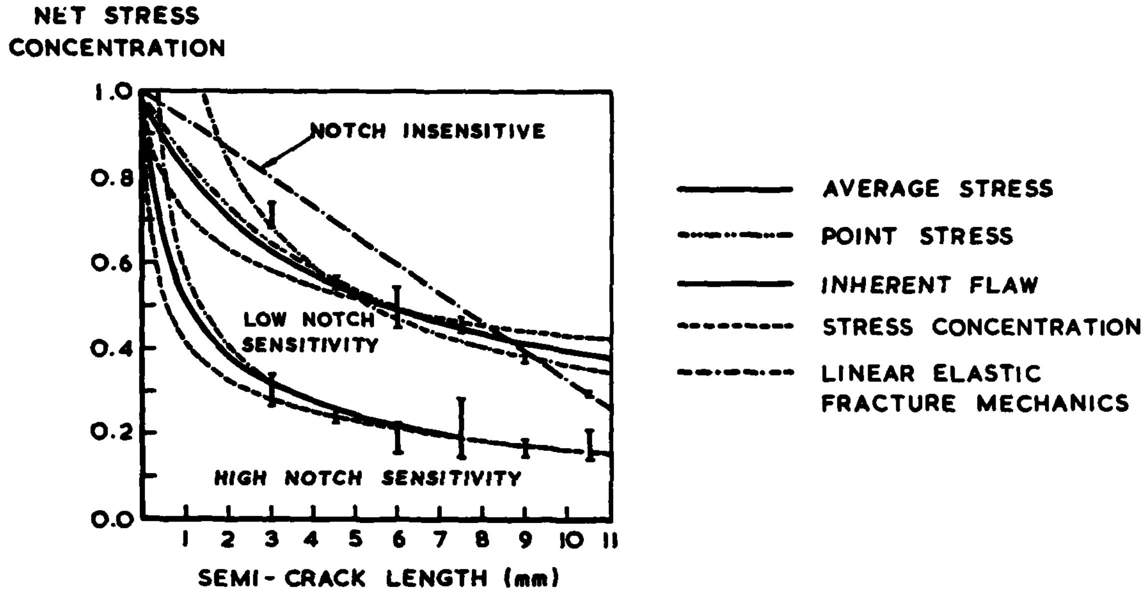

Fig 14 Stress concentrations due to notches predicted using various models and compared with experimental results for two different CFRP laminates under tension (R.J. Lee, D.C. Phillips)

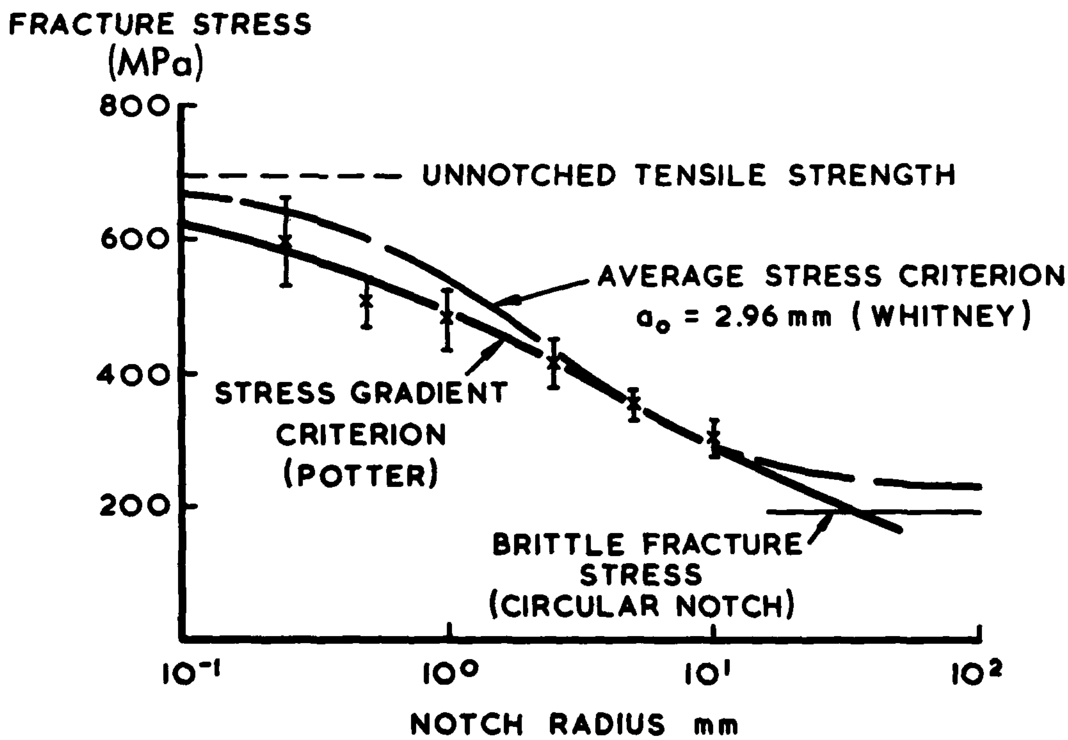

Fig 15 Comparison of values of notched tensile strength predicted using the stress gradient and average stress criteria, and obtained experimentally (R.T. Potter)

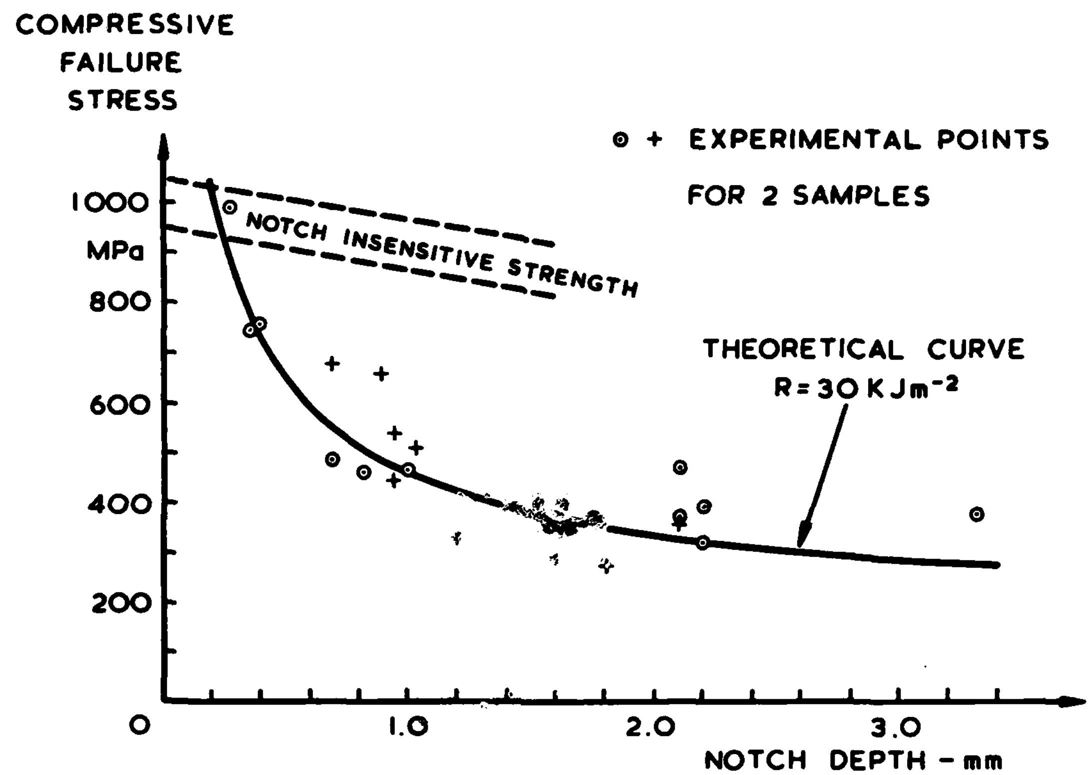

Fig 16 Comparison of values of notched strength for unidirectional CFRP under compression predicted using a linear elastic fracture mechanics approach, and obtained experimentally (C.R. Chaplin)

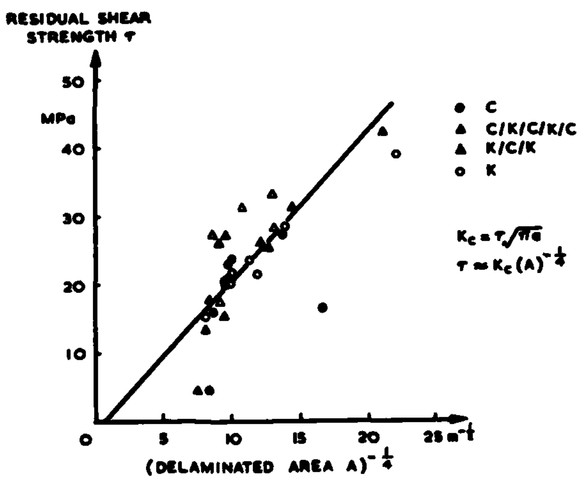

Fig 17 Residual shear strength related to delaminated area following impact for carbon fibre, Kevlar fibre and hybrid reinforced plastics (G. Dorey, *et al*)

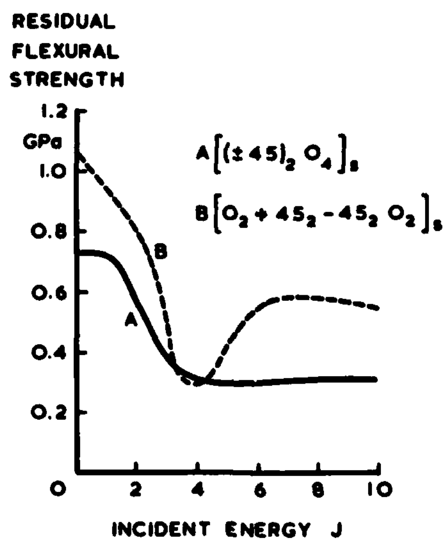

Fig 18 Residual flexural strength of CFRP showing effect of delamination for low incident energies, flexural failure of 0^0 fibres at 3-4 J for lay-up B and penetration at higher energies (G. Dorey)

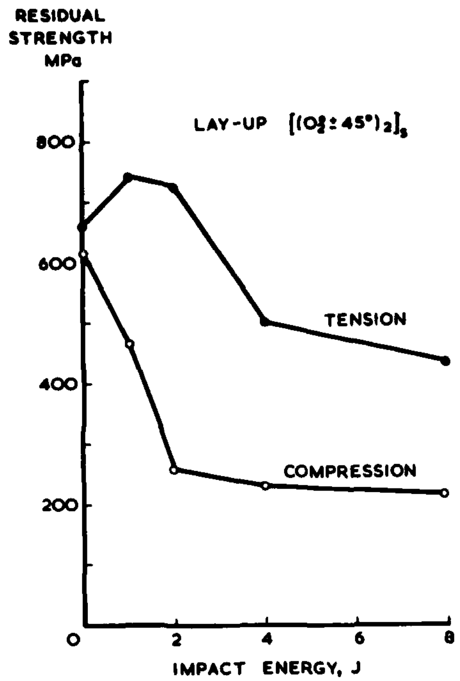

Fig 19 Residual tensile and compressive strengths of CFRP showing effect of delamination at low impact energies and flexural failure of 0° fibres at higher energies (G. Dorey, D.J. Portsmouth)

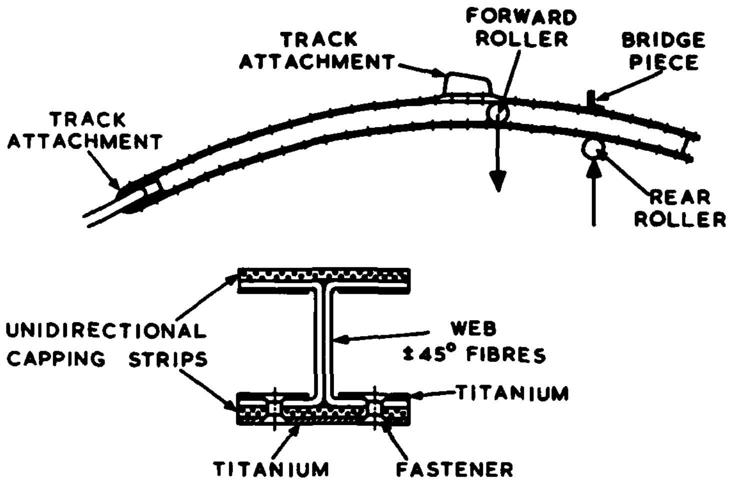

Fig 20 Construction of carbon-fibre wing flap track (BAe, Manchester)

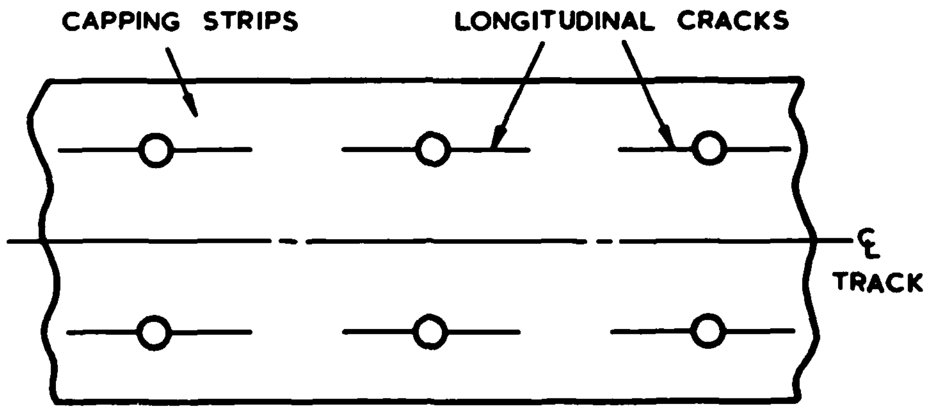

Fig 21 Cracking between fastener holes in capping strips (BAe, Manchester)

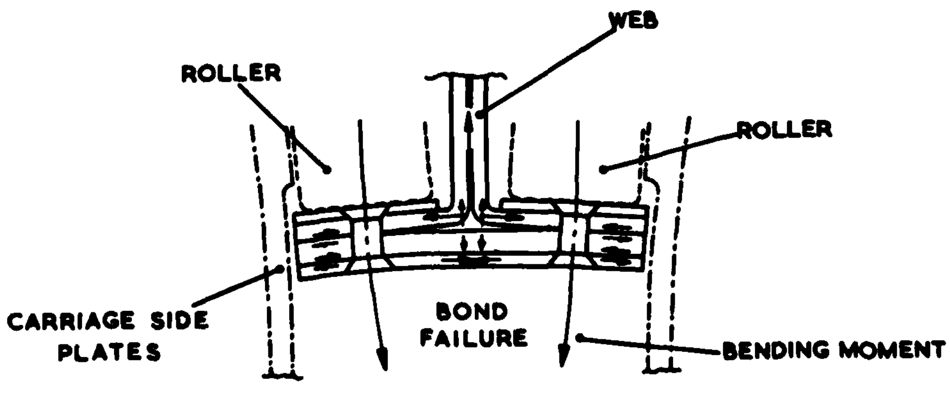

Fig 22 Bond failure at forward roller position (BAe, Manchester)

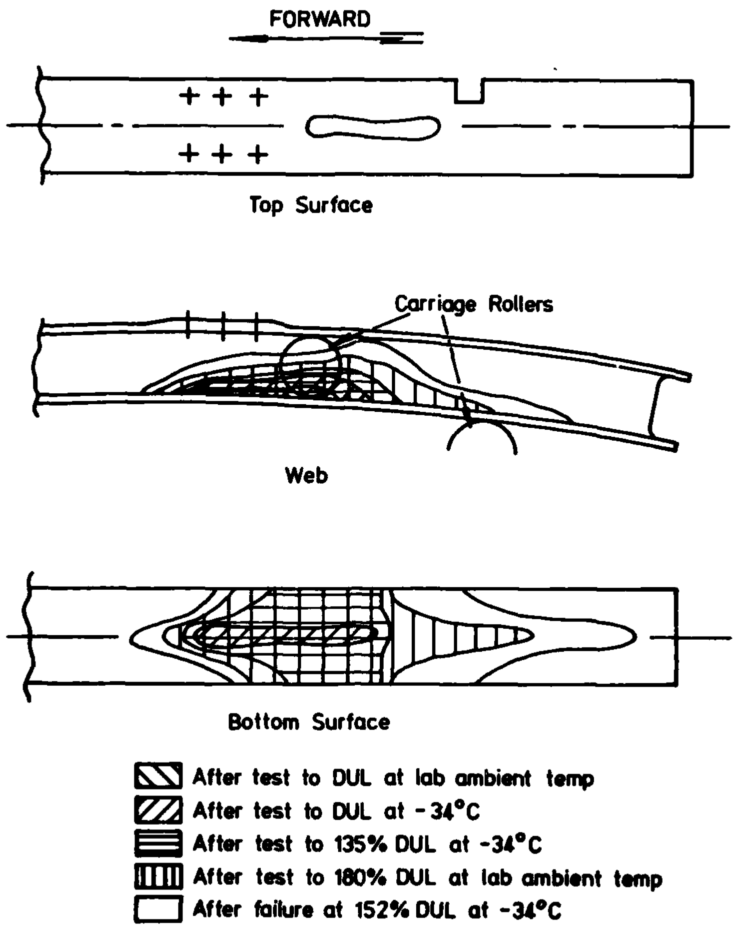

Fig 23 Damage to flap track after various loadings (BAe, Manchester)

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14. Abstract

In the United Kingdom, research on defects in composites is being carried out in government research establishments, aerospace industries and universities. Defects produced during manufacture, cracking produced during loading and in-service damage such as impact have been studied together with their effects on mechanical properties and their implications for structural design. There is also work modelling the behaviour of notched composites and on the design of composites to give improved toughness and increased tolerance to damage.

A review of research in the United Kingdom is given based on papers presented at a meeting of the Institute of Physics held in November 1979 on "the significance of defects on the failure of fibre composites" and on more recent work.

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